

Simulation model of unity power factor uninterruptible power supply topology using single-phase matrix converter

Muhammad Shawwal Mohamad Rawi, Rahimi Baharom, Nur Hidayah Abdullah

Power Electronics Research Group (PERG), School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Selangor, Malaysia

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ABSTRACT

This paper presents a computer simulation model of the unity power factor uninterruptible power supply (UPS) topology using single-phase matrix converter (SPMC) that focuses on the switching integration for both rectifier and inverter operations. The proposed integrated switches capable of controlling the SPMC to operate as a rectifier operation to charge the DC battery during the normal operation and to switch the SPMC to operate as an inverter during power outage conditions continuously and instantaneously using a single power converter circuit. The use of a single power converter circuit can solve the typical UPS system that requires at least two separate power converter circuits, thus contributing to the higher power semiconductor losses and complicated control circuits. With the proposed circuit topology, it can improve the power density of the power electronics converter system resulting in low power losses. The active power filter (APF) function has been used to improve the supply current waveform to follow the shape of the sinusoidal reference current to be in phase with the supply voltage waveform, thus reduce the total harmonic distortion (THD) level and improve the power factor. To verify the proposed operation, the selected simulation results are presented, and the proposed work has been done through the MATLAB/Simulink.

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Corresponding Author:

Rahimi Baharom

Power Electronics Research Group (PERG), School of Electrical Engineering, College of Engineering

Universiti Teknologi MARA

40450 Shah Alam, Malaysia

Email: rahimi6579@gmail.com

1. INTRODUCTION

As Malaysia moves towards high-income countries and achieves developed countries, a fourth industry revolution (IR 4.0), has been formulated by implementing the Manufacturing industry transformation for the manufacturing sector and as a result, will be able to support Malaysia's commitment to meet the United Nations Goal 9 and Goal 12 of the Sustainable Development Goals (SDGs) [1]. This is in line with the 7th Core of the Eleventh Malaysia Plan (RMK-11) blueprint that highlights infrastructure strengthening via effective sourcing and energy delivery to ensure energy sustainability [2]. The increased use of uninterruptible power supply (UPS) has recently been sparked due to the revolution of the global manufacturing sector that requires high power quality and high power reliability that would enable to prevent any power disruption, especially for a critical load [3], [4]. Despite power system reliability, the high-quality power supply is also important to cater to sensitive equipment that couldn't optimize their operation and could affect device destruction and malfunction due to the harmonics penetration [5].

Conventionally, there are three key types of UPS system design such as online double conversion, line-interactive and offline (standby and battery backup), and have been described in [6]. The on-line UPS able to perform double conversion [7] in which the accepted AC input supply is rectifying to DC through a rechargeable battery and supply inverting back to AC source. The inverter is kept in line for line-interactive and redirects the DC current path to supply the load when power lost. Off-line which is as a standby mode that powered up the load directly by the input power and only operate when the power fails. The disadvantage of on-line UPS system are low level of dynamic characteristic-negative quality of transient at switching [8].

The typical static UPS system consists of three main units which is an inverter, rectifier, and a static bypass switch as show in Figure 1. The static bypass switch is used to connect the DC source (battery) to the loads that function as the backup supply and isolate from the main AC source until the main supply is reconnected to the grid. In the rectifier unit consist a bridge-diode circuit without connecting any additional control function [9], [10], thus, it is very difficult to ensure the input sinusoidal of the current and volage supply to be in phase without the help of PFC technique [11]-[13]. Since the conventional UPS system uses the combination of three separate units of rectifier, inverter, and static bypass switch, it could lead to the bulky size of the system. In addition, without any additional control function, the typical circuit topology will generate high harmonic, hence, resulting in low power factor. The matrix converter (MC) can be classified as the best solution for AC-AC conversion [8]. The topology of MC was first described by Gyugyi in 1976 and has been reviewed in [14], where it operates in all four quadrants switching operation [15]. These superiorities make the MC an appropriate alternative to the traditional voltage source inverter [12]. The single-phase matrix converter (SPMC) was first realized by Zuckerberger *et al.* [11]. The subsequent further works have shown that it is possible to synthesize SPMC with possible boost converter functions with various inputs (AC/DC) and outputs (DC/AC) [15]-[18]. The SPMC requires 4 bi-directional switches as shown in Figure 2.

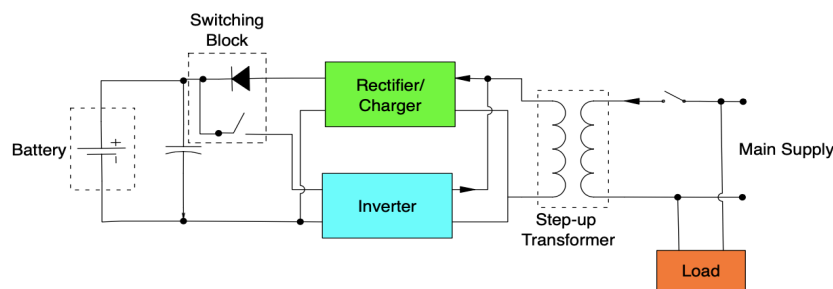


Figure 1. Typical static UPS system

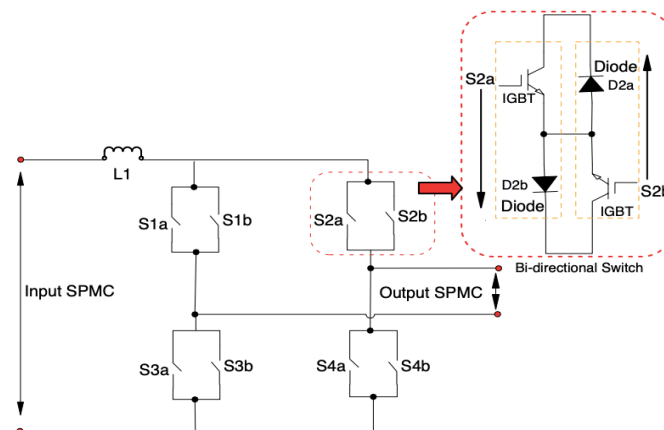


Figure 2. SPMC circuit topology and bi-directional switch

It requires the use of bidirectional switches capable of blocking voltage and conducting current in both directions [19]. In MC, most of the bidirectional switches use a common emitter (IGBT) and diode pair. IGBTs have been widely used among researchers since their introduction because they are capable of operating on high-powered applications with switching frequencies that are fast enough for fine-grained control [20]. In

common converters, in order to dissolve inductive energy to free-wheel to the resistive load, the free-wheeling diodes are applied. However, free-wheeling diodes do not exist in SPMC, a consequence switching technique needs to be developed to enable forced controlled free-wheeling. This technique is applied to defend the converter from any harm because of voltage and current spikes.

The previous publication on SPMC describes an alternative topology for the fully controlled rectifier and inverter operations with various loads studies such as pure resistive (R), inductive (RL) and capacitive (RC). Apart from the circuit topology, the control algorithms for the rectifier and inverter operations using SPMC with the safe commutation strategies to eliminate the voltage and current spikes that may cause damage on switching devices have been discussed in [6], [13], [21]. In 2006, the application of SPMC to operate as a UPS system has been proposed in [22]. However, this paper does not discuss in detail the operation of switching integration for the rectifier and inverter transition during the normal and power outage conditions. The recent publication on the UPS system using SPMC topology has been proposed in [23], with the details explanation on the switching integration algorithms for the rectifier and inverter operation. But this paper does not include the function of the active power filter (APF) function that could result in the high total harmonic distortion (THD) level with the lower power factor.

Therefore, this paper proposes a comprehensive presentation to enhance the previous work on the UPS operation by focusing on the switching integration for both rectifier and inverter operation including the safe-commutation and APF function to reduce the THD level thus improving the power factor of the system. The benefits of a proposed single-phase UPS system are preserved, such as a smaller number of power devices and low power losses. Nonetheless, the main important feature of the proposed single-phase UPS system is the fact that the whole system uses only a single circuit topology to perform both rectifier and inverter operations by using safe-commutation strategies [24] and current control loop (CCL) strategies [25]. This attribute to the high-power density power converter system, which is in-line with the power electronics technological roadmap to reduce the losses, cost, size of UPS and volume. The proposed system implemented with development of a new UPS simulation model by using simulation MATLAB/Simulink.

2. OPERATION OF CONTROLLED RECTIFIER WITH APF FUNCTION

The operation stage of the rectifier has been realized as a fully controllable rectifier for charging operation using a current control loop (CCL) as shown in Figure 3 and switching algorithms as shown in Table 1. The AC supply current with the current compensation strategy has been used to correct the pulsating properties of the rectifier input current with a capacitor output filter. The control electronic drive by CCL was used to generate active pulse width modulation (APWM) signal. These strategies are implemented using the boost technique to acquire in phase the supply current and the supply voltage. Results of this technique improve the power factor and reduce the THD level. The APWM switching pulse signal using CCL is as shown in Figure 4 [13].

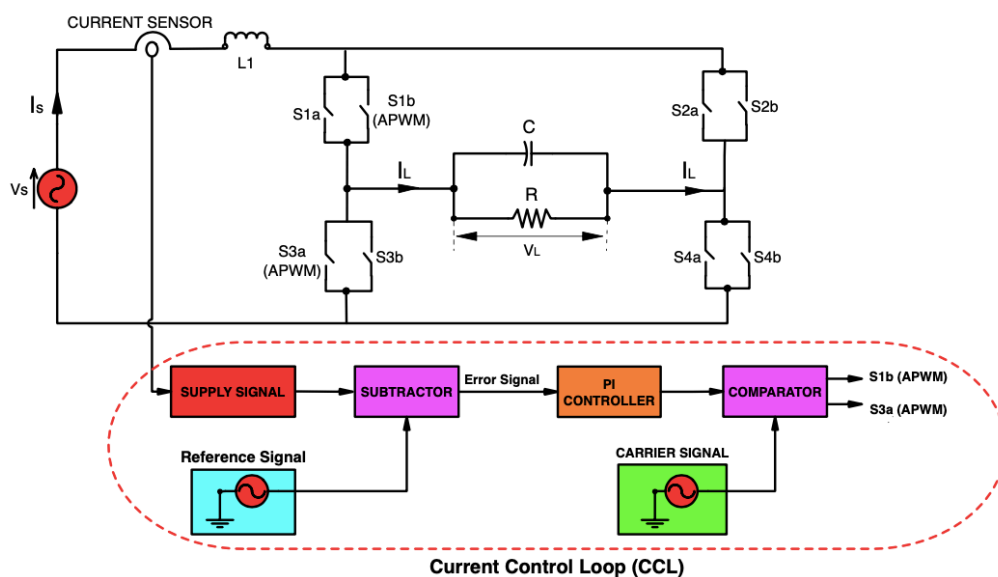


Figure 3. SPMC circuit with CCL

Table 1. Switching algorithm of rectifier with CCL

| Rectifier switches | Current control switching | |
|--------------------|---------------------------|----------------|
| | Positive cycle | Negative cycle |
| S1a | ON | Off |
| S1b | Off | APWM |
| S2a | Off | Off |
| S2b | Off | ON |
| S3a | APWM | Off |
| S3b | Off | ON |

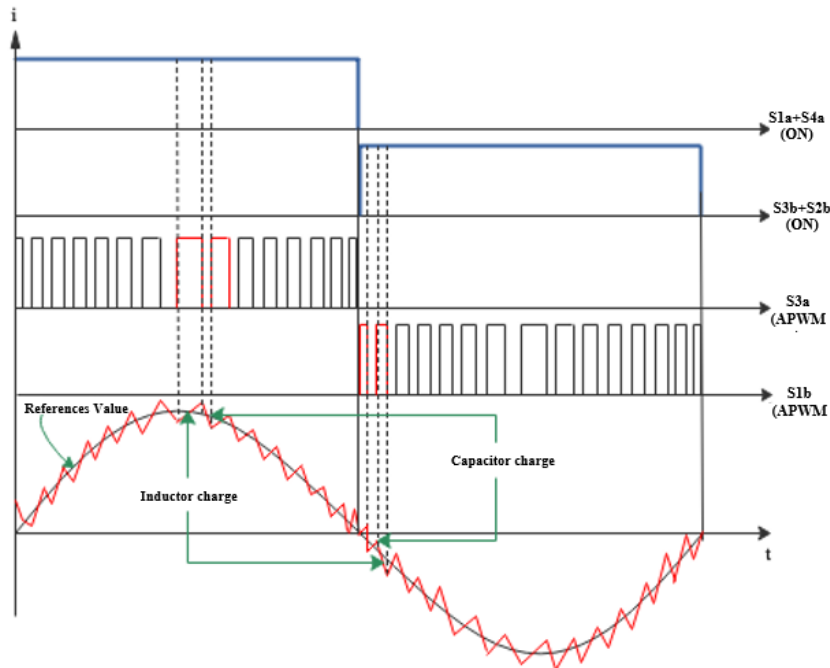


Figure 4. Filter power unit function

The operation of APF is to force the supply current to follow the reference current (I_{ref}). I_{ref} is set according to the maximum amplitude of the distorted supply current waveform obtained from the same rectifier operation without any filters function. In CCL, for the first stage, a subtractor is used to subtract the sensed supply current with the sinusoidal reference current to produce an error signal. This stage is to configure the sinusoidal reference current and will improve the sensed current with a quick response to any changes at the load. In the second stage, the comparator is used to compare the output proportional integral (PI) controller with the carrier signal that determines the switching frequency to produce the APWM signal to control switches S3a and S1b. In the positive cycle operation mode, the supply current flows through the pair of switches S1a and S3a where S3a is controlled by the APWM signal from the output of CCL. In this mode of operation, the line inductor (L) starts charging the energy until the supply current value achieves more than the reference current value. When the appropriate pair of switches S1a and S4a is turned ON, the capacitor load is charging while the line inductor (L) is discharging until the supply current is below the reference current value. In the negative cycle operation, the supply current flows through the pair of switches S3a and S1a for charging the line inductor (L) where S1a is controlled by the APWM signal from the output of CCL. While the appropriate pair of switches S3b and S2b is turned ON for capacitor charging while the line inductor (L) is in the discharging operation. As a result, the output voltage at the capacitor load drops, the capacitor discharge through the load, and a ripple voltage (V_{ripple}) appears on the output voltage and can be determined as:

$$V_{ripple} = \frac{I_{load}}{2fc} \quad (1)$$

3. INVERTER (DC-AC) OPERATION

The operational stage of the inverter operation occurs when the pair of switches S1a and S4a turn ON, as shown in Figure 5. During this time interval, the supply current flow from the positive terminal of DC source

to the load through switch S1a, then, return back to the negative terminal of DC source through switch S4a. Currently, the DC source (standby battery) transfers energy to the AC load, performing an inverter operation for the positive half-cycle. This circuit configuration has duration δT_s , where δ corresponds to duty cycle of the pair of switches S1a and S4a. The second operational stage starts when the pair of switches S1a and S4a turn OFF, and the pair of switches S2a and S3a turn ON instantaneous and simultaneously as shown in Figure 6. In this stage, the energy in DC source is transferred to the AC load through switch S2a and return back to the negative terminal through switch S3a. Again, the DC source transfers energy to the AC load, performing an inverter operation for the negative half-cycle. This circuit has duration $(1-\delta) T_s$ where δ corresponds to duty cycle of the pair of switches S2a and S3a.

$$T_s = \frac{1}{f_s} \quad (2)$$

Where f_s is the switching frequency and T_s is the one full cycle of the switching period. From the DC-AC operation stages, it can be seen that the input DC voltage can be converted into an AC form using SPMC with proper control of switches based on the switching algorithms as tabulated in Table 2. A desired output AC voltage can be obtained using a purely resistive load. However, with an inductive load, the commutation problem might be happened due to the short-circuit path during switches transition, thus, voltage spikes are induced. This can cause damage to the converter power switches because the resulting voltage spike is usually twice or more than the supply voltage value and depends on the value of an inductor. To solve the commutation problem, a safe-commutation strategy will be developed by creating the dissipation path for the energy stored in an inductor to fully dissipate during the switch dissipations process by eliminated the induced voltage spike occurred in system. This method does not require any addition of electronic components such as snubber capacitors as have been proposed by other researchers.

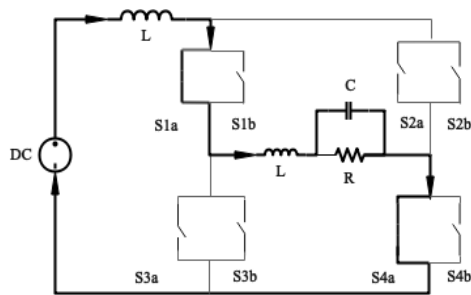


Figure 5. The operational stages of DC-AC converter for positive cycle operation

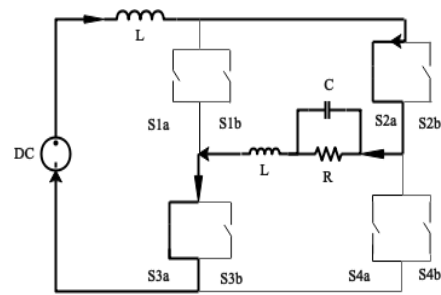


Figure 6. The operational stages of DC-AC converter for negative cycle operation.

Table 2. Switching algorithm for DC-AC operation

| Rectifier switches | Without Safe-Commutation | | With Safe-Commutation | |
|--------------------|--------------------------|----------------|-----------------------|----------------|
| | Positive cycle | Negative cycle | Positive cycle | Negative cycle |
| S1a | SPWM | Off | SPWM | Off |
| S1b | Off | Off | Off | Off |
| S2a | Off | Off | Off | SPWM |
| S2b | Off | SPWM | Off | Off |
| S3a | Off | Off | Off | ON |
| S3b | Off | SPWM | ON | Off |
| S4a | SPWM | Off | ON | Off |
| S4b | Off | Off | Off | ON |

4. INTEGRATED SWITCHING ALGORITHM OF UNINTERRUPTIBLE POWER SUPPLY WITH ACTIVE POWER FILTER FUNCTION

The UPS topology using SPMC topology has been developed is based on improved version of the typical UPS as shown in Figure 7. The SPMC will perform all the three functions of inverter, rectifier and blocking switch. The added feature has been implemented in the form of supply side unity power factor operation, active filter and reactive compensation. The benefits of the proposed single-phase UPS system are preserved, such as a smaller number of power devices and low power losses. Nonetheless, the main important feature of the proposed new advancement of single-phase UPS system is the fact that the whole system uses only a single circuit topology to perform both rectifier and inverter operations. This attribute to the high-power

density power converter system, which is in-line with the power electronics technological roadmap to reduce the losses, size, volume, and cost.

The proposed UPS system using the SPMC has fully controllable rectifying and inverting stages [26]. The operation of UPS integrated with an APF function can be divided into two modes of operations which are rectifying and inverting modes by using a single circuit topology of the SPMC. The rectifier mode rectified an AC power supply to the DC form. During positive cycle operation, the line inductor charges during the pair of switches S1a and S3a (APWM) turned ON, and the power starts to be transferred from AC to the DC side when the pair of switches S1a and S4a turn ON whilst switch S3a turns OFF. During negative cycle operation, the supply current flows through the pair of switches S3b and S1a (APWM), the line inductor is charging, and the power transferred to the DC side when the pair of switches S3b and S2b are turned ON whilst S1b is turned OFF. The inverter mode inverted DC power supply to an AC load. During positive cycle operation, the pair of switches S1a and S4a are turned ON allowing the current flow from the DC source to the AC load. For the negative cycle operation, the pair of switches S2a and S3a turned ON allowing the current flow from the DC source to the AC load.

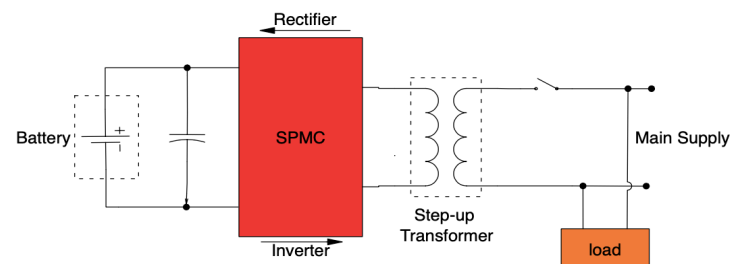


Figure 7. The UPS system using SPMC

5. COMPUTER SIMULATION MODEL USING MATLAB/SIMULINK

The computer simulation model of the proposed UPS uses the MATLAB/Simulink simulation tool. Table 3 shows the parameters used to simulate the rectifier operation. Figure 8 shows the PWM generator for the safe-commutation technique to produce a PWM output signal by comparing the carrier signal (repeating sequence block) which produces sawtooth waveform to the constant that represent a straight-line reference signal through a relational operator. Then the PWM output signal is multiplied with the output signal of phase detector as in Figure 9 to produce a positive and negative pulse waveform.

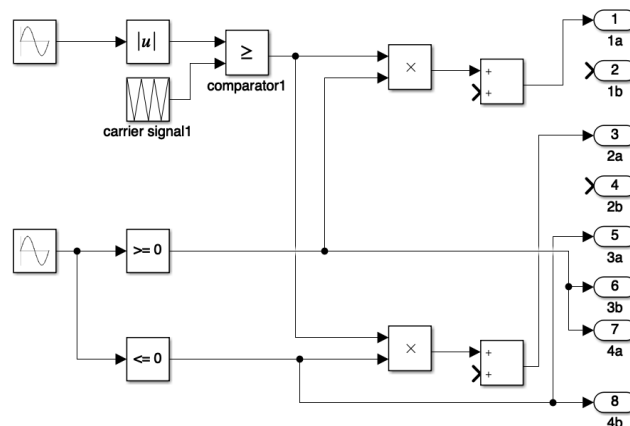


Figure 8. PWM generator with safe commutation

The block 'more than zero' represent the 'ON' pulse for positive cycle while block 'less than zero' represent the 'ON' pulse for negative cycle operation. The 'Add' block is added to the PWM generator circuit in order to integrate the PWM signal and the output signal from the phase detector. Figure 10 shows the rectifier integrated with the power factor correction or CCL and interconnecting with the parallel RC load.

Table 3. Circuit parameter of rectifier incorporating with PFC

| Parameter | Value |
|----------------------------|---------------|
| Supply voltage, V_s | 100 V |
| Boost inductor, L_s | 4 mH |
| Inductor load, L_L | 100 mH |
| Capacitor load, C_L | 0.01 μ F |
| Resistive load, R_L | 2000 Ω |
| Switching frequency, f_s | 10 kHz |
| Proportional gain, K_p | 8 |
| Integral gain, K_i | 27 |

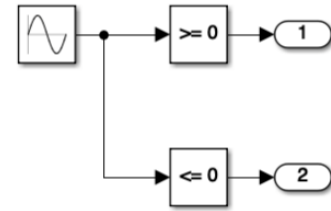


Figure 9. Phase detector circuit

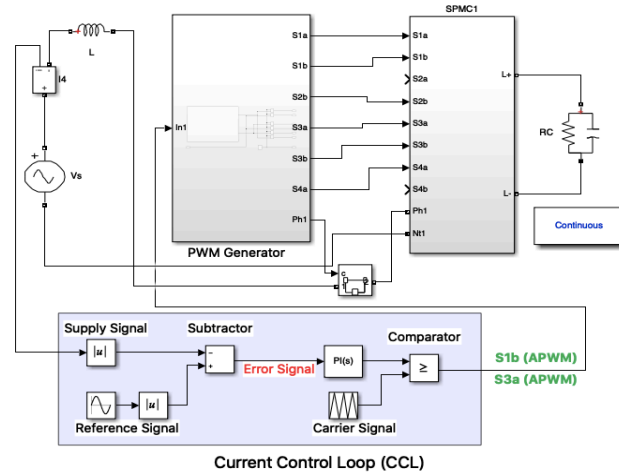


Figure 10. Rectifier circuit with current control loop (CCL) circuit

The inverter operation was simulated using switching state of SPMC with the safe-commutation strategy. The parameters regarding to the inverter operation is tabulated in Table 4. In order to perform the proposed a new UPS system, the AC-DC converter and DC-AC converter that have been developed in the previous subsection are integrated with a proper switching algorithm. For this purpose, the step response is being used to simulate the sample time changing between the rectifier and inverter operations. This is to investigate during the AC power supply is lost, the DC supply can be a backup power supply for the temporary transfer of current to the load. Figure 11 shows the circuit simulation model of the proposed UPS system using the SPMC circuit topology in the MATLAB/Simulink. Two controllers to control the rectifier and inverter configuration circuits have been used to run the UPS system. Figures 12 and 13 show the circuit breaker for the rectifier and inverter operations.

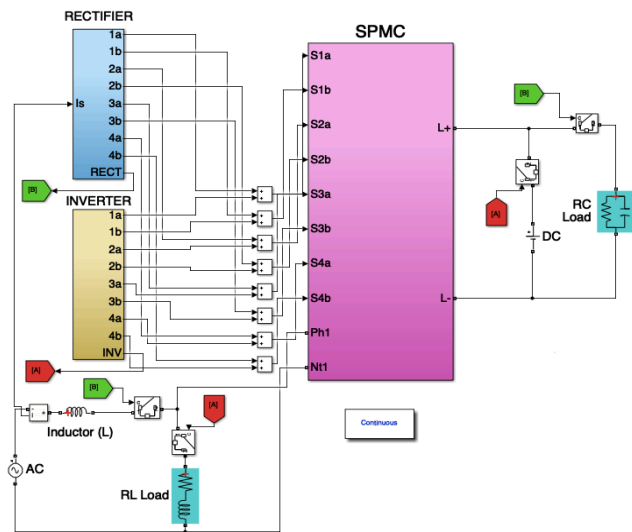


Figure 11. UPS with PFC circuit

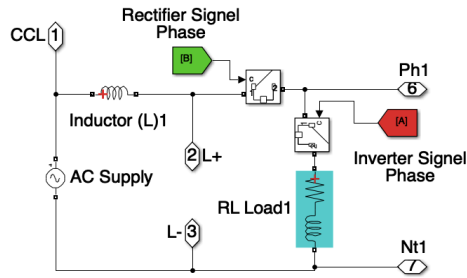


Figure 12. Breaker for rectifier operation in UPS system

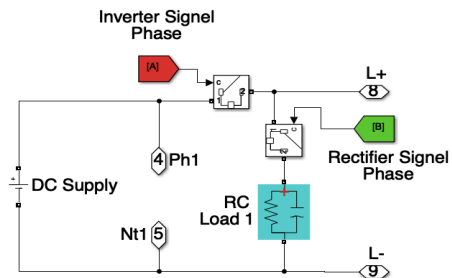


Figure 13. Breaker for inverter operation in UPS system

Table 4. Circuit parameter of inverter

| Parameter | Value |
|----------------------------|---------------|
| Input Voltage, V_s | 100 V |
| Inductor Load, L_l | 100 mH |
| Resistive load, R_L | 2000 Ω |
| Capacitive, CL | 0.01 μ F |
| Switching Frequency, f_s | 10 kHz |

6. RESULTS AND DISCUSSION

The input current waveform of rectifier operation using RC load is as shown in Figure 14. Based on the distorted supply current analysis, it shows the THD level of 267.31%. The high THD level can affect the low power factor resulting in high power losses. Figure 15 shows the output voltage of the RC load for the rectifier operation with a low output voltage ripple. The CCL is introduced to improve the power factor and to give an uninterrupted supply to the load. The proposed CCL in rectifier operation makes the supply current in phase with the supply voltage as shown in Figure 16. The THD level reduces to 1.11% which is below 8% and fulfills the IEEE 519-2014 Standard. Figure 17 shows the supply current, I (red waveform) force to follow the reference current signal (blue waveform) for the AC-DC converter integrated with the CCL.

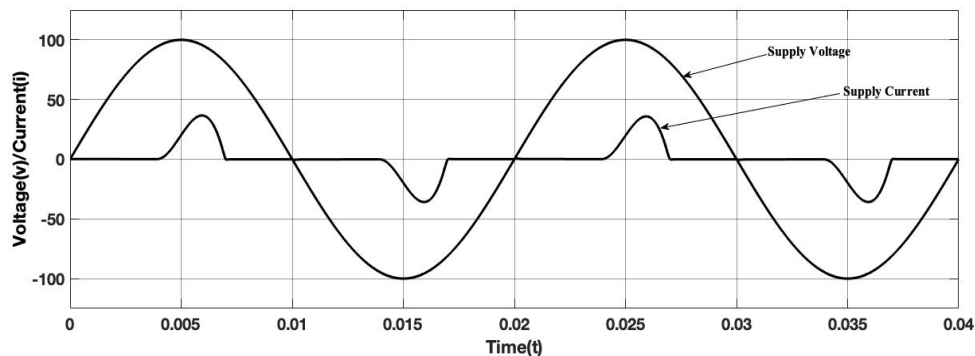


Figure 14. Input current waveform without APF function ($V_s:I_s=1:1/10$)

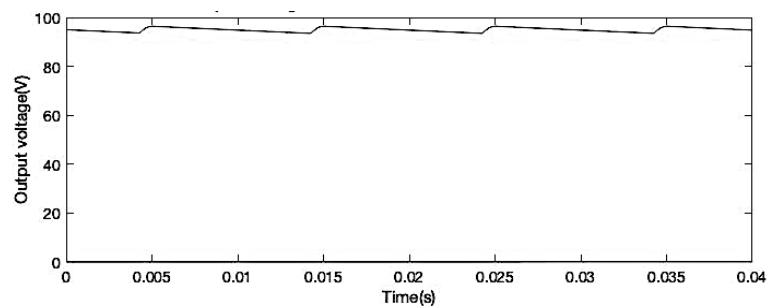


Figure 15. Output voltage waveform for rectifier with APF

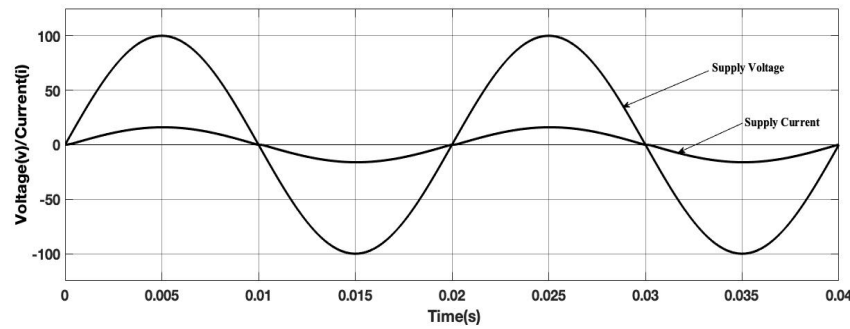


Figure 16. Input current and voltage waveforms for the rectifier operation with the APF function ($V_s:I_s=1:1/10$)

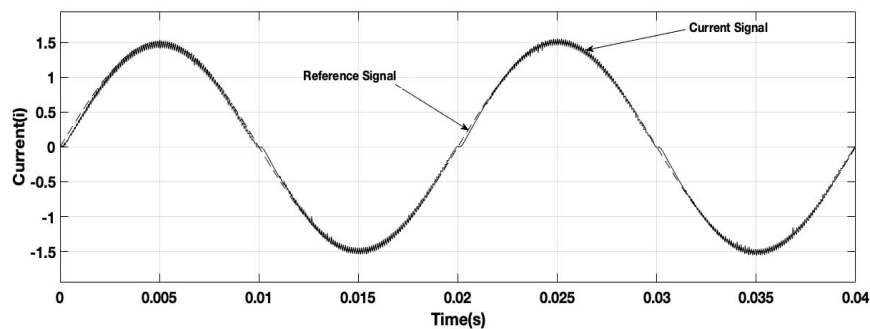


Figure 17. Supply current waveform force follow the reference current signal in APF function

For the proposed UPS operation, the step response was used in the circuit to provide the different simulation time between the rectifier and inverter operations. During the normal operation of the UPS, the rectifier will be operated from time 0 to 0.08ms, while for the inverter operation, it will start at 0.08ms. The initial value of step response for rectifier operation is set as '1' and the final value is '0'. Figures 18 and 19 show the waveform of the proposed UPS system during the charging and discharging mode of operations. AC supply current with the compensation strategy has been implemented to correct the pulsating properties of rectifier input current due to the non-linear load. During the battery charging process (rectifier operation) from 0 to 0.08s, the AC supply voltage is converted to the output DC form as shown in Figures 18 and 19. The power outage condition has been considered from 0.08s, and during this time the inverter operation will take part in inverting the DC voltage from the backup battery to the output AC form as shown in Figures 18 and 19.

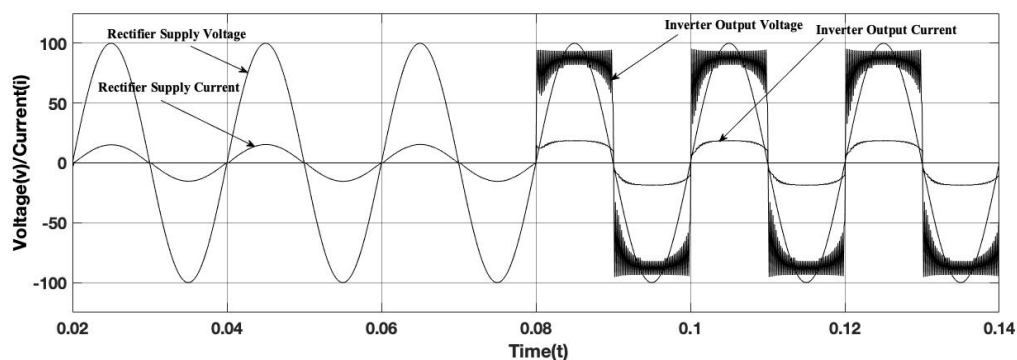


Figure 18. UPS input voltage and current waveforms for rectifier operation (0.02 to 0.08s) and the inverter operation (0.08s to 0.14s)

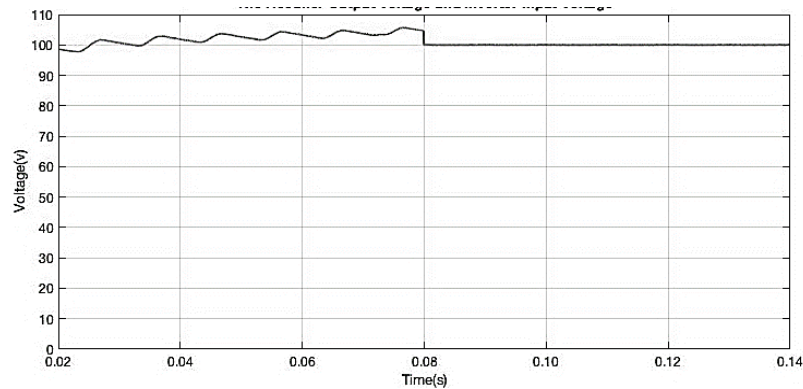


Figure 19. UPS output voltage waveform of rectifier operation (0.02s to 0.08s) and input voltage of an inverter operation (0.08s to 0.14s)

7. CONCLUSION

This paper briefly discussed the operation of the UPS system using the SPMC topology. Since, the UPS system has been implemented using a single SPMC circuit topology, thus, it can provide an alternative to the conventional circuit topology that uses at least two separate circuits. As a result, this contributes to the high-power density of the power converter system, which is in-line with the power electronics technological roadmap. The operation of the UPS system with the new integrated switching algorithms has been verified during all the possible operating conditions, i.e., normal and power outage. Despite improving the power density, the system also has the capability to maintain unity power factor operation of the supply current waveform with an APF function. The UPS system has been successfully developed by using the MATLAB/Simulink simulation tool. The switching commutation strategies have been constructed to solve the commutation problem of occurrence in voltage spikes caused by the appearance of inductive load. As a result, such new enhancements can be used as a good foundation of future power electronic converters system through compact and high-power density features.

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REFERENCES

- [1] Malaysian Ministry of International Trade and Industry, "Industry4WRD National Policy on Industry 4.0," 2019.
- [2] Malaysian Federal Government Administrative Centre, Director General, Economic Planning Unit, Prime Minister's Department "Eleventh Malaysia Plan (RMK-11) Blueprint," 2015.
- [3] N. Vazquez, C. Aguilar, J. Arau, R. O. Caceres, I. Barbi and J. A. Gallegos, "A novel uninterruptible power supply system with active power factor correction," in *IEEE Transactions on Power Electronics*, vol. 17, no. 3, pp. 405-412, 2002, doi: 10.1109/TPEL.2002.1004248.
- [4] S. Abaray, S. Beaver and C. Nguyen, "How Reliable Is Your Uninterruptible Power System?: Eliminating Single Points of Failure," in *IEEE Industry Applications Magazine*, vol. 25, no. 4, pp. 59-65, 2019, doi: 10.1109/MIAS.2018.2875179.
- [5] E. R. da Silva, W. R. dos Santos, C. B. Jacobina and A. C. Oliveira, "Single-phase uninterruptible power system topology concepts: Application to an universal active filter," *2011 IEEE Energy Conversion Congress and Exposition*, pp. 3179-3185, 2011, doi: 10.1109/ECCE.2011.6064197.
- [6] R. Baharom and M. K. Hamzah, "A New Single-Phase Controlled Rectifier Using Single-Phase Matrix Converter Topology Incorporating Active Power Filter," *2007 IEEE International Electric Machines & Drives Conference*, pp. 874-879, 2007, doi: 10.1109/IEMDC.2007.382784.
- [7] P. M. Curtis, *Maintaining Mission Critical Systems in a 24/7 Environment*, Hoboken, NJ: Wiley-IEEE Press, 2021.
- [8] V. Yaskiv and R. Hirnyak, "The comparative analysis of UPS topology," *Proceedings of the International Conference Modern Problems of Radio Engineering, Telecommunications and Computer Science*, 2004., 2004, pp. 520-521.
- [9] J. Kim, H. H. Choi and J. Jung, "MRAC-Based Voltage Controller for Three-Phase CVCF Inverters to Attenuate Parameter Uncertainties Under Critical Load Conditions," in *IEEE Transactions on Power Electronics*, vol. 35, no. 1, pp. 1002-1013, 2020, doi: 10.1109/TPEL.2019.2912393.
- [10] S. Gong, J. Huang, and G. He, "Research on ADRC controller design for three-phase UPS with multi-disturbances," *The Journal of Engineering*, pp. 8409-8413, 2019, doi: 10.1049/joe.2019.1105.
- [11] A. Zuckerberger, D. Weinstock, and A. Aiexandrovitz, "Single-phase matrix converter," *IEE Proc. Electr. Power Appl.*, vol. 144, no. 4, pp. 235-240, 1997, doi:10.1049/ip-epa:19970848.
- [12] M. E. De Oliveira Filho, E. R. Filho, K. E. B. Quindere and J. R. Gazoli, "A Simple Current Control for Matrix Converter," *Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting*, pp. 2090-2094, 2006, doi: 10.1109/IAS.2006.256823.




- [13] N. Burany, "Safe control of four-quadrant switches," *Conference Record of the IEEE Industry Applications Society Annual Meeting*, 1989, pp. 1190-1194 vol.1, doi: 10.1109/IAS.1989.96794.
- [14] R. Alammari, Z. Aleem, A. Iqbal, and S. Winberg, "Matrix converters for electric power conversion: Review of topologies and basic control techniques," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 10, 2019, doi: 10.1002/2050-7038.12063.
- [15] G. Aarthi and T. Porselvi, "Modeling and simulation of Single Phase Matrix Converter using PWM," *2012 International Conference on Computing, Electronics and Electrical Technologies (ICCEET)*, 2012, pp. 168-173, doi: 10.1109/ICCEET.2012.6203883.
- [16] Z. Idris and M. K. Hamzah, "Implementation of a new Single-phase Cycloconverter based on Single-phase Matrix Converter Topology using Sinusoidal Pulse Width Modulation with Passive Load Condit," *2006 1ST IEEE Conference on Industrial Electronics and Applications*, 2006, pp. 1-6, doi: 10.1109/ICIEA.2006.257158.
- [17] R. Blundell, L. Kupka, and S. Spiteri, "AC-DC converter with unity power factor and minimum harmonic content of line current: Design considerations," *IEE Proc. Electr. Power Appl.*, vol. 145, no. 6, pp 553-558, 1998, doi:10.1049/ip-epa:19982337.
- [18] W. E. Reid, "Power quality issues-standards and guidelines," in *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 625-632, 1996, doi: 10.1109/28.502175.
- [19] S. H. Hosseini and E. Babaei, "A new generalized direct matrix converter," *ISIE 2001. 2001 IEEE International Symposium on Industrial Electronics Proceedings (Cat. No.01TH8570)*, vol. 2, pp. 1071-1076, 2001, doi: 10.1109/ISIE.2001.931624.
- [20] M. J. Bland, P. W. Wheeler, J. C. Clare and L. Empringham, "Comparison of bi-directional switch components for direct AC-AC converters," *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*, vol. 4, pp. 2905-2909, 2004, doi: 10.1109/PESC.2004.1355295.
- [21] M. K. Hamzah, S. Z. M. Noor and S. F. A. Shukor, "A New Single-Phase Inverter using Single-Phase Matrix Converter Topology," *2006 IEEE International Power and Energy Conference*, 2006, pp. 459-464, doi: 10.1109/PECON.2006.346695.
- [22] M. K. Hamzah, M. F. Saidon, and S. Z. M. Noor, "Application of Single Phase Matrix Converter Topology in Uninterruptible Power Supply Circuit incorporating Unity Power Factor Control," *2006 1ST IEEE Conference on Industrial Electronics and Applications*, 2006, pp. 1-6, doi: 10.1109/ICIEA.2006.257189.
- [23] R. Baharom, M. S. M. Rawi, and N. Farahaida Abd Rahman, "Uninterruptible Power Supply Employing Single-Phase Matrix Converter Topology," *2020 IEEE International Conference on Power and Energy (PECon)*, 2020, pp. 19-23, doi: 10.1109/PECon48942.2020.9314528.
- [24] S. Z. M. Noor, R. Baharom, M. K. Hamzah and N. R. Hamzah, "Safe-commutation strategy for controlled rectifier operation using single-phase matrix converter," *2009 International Conference on Power Electronics and Drive Systems (JPEDS)*, 2009, pp. 1026-1029, doi: 10.1109/PEDS.2009.5385720.
- [25] R. Baharom, M. Z. Rosman, I. Yassin and N. F. Abdul Rahman, "Development of Single-Phase Active Power Filter Using Current Source Inverter (CSI)," *2019 IEEE 9th Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, 2019, pp. 64-68, doi: 10.1109/ISCAIE.2019.8743834.
- [26] R. Baharom, M. K. M. Salleh, M. N. Seroji and M. K. Hamzah, "A high power factor bidirectional battery charger using single-phase matrix converter," *2015 IEEE 10th Conference on Industrial Electronics and Applications (ICIEA)*, 2015, pp. 1397-1402, doi: 10.1109/ICIEA.2015.7334327.

BIOGRAPHIES OF AUTHORS






Muhammad Shawwal Mohamad Rawi    is a postgraduate student in School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Malaysia since 2020. He is a senior assistant director under Department of Skills Development, Ministry of Human Resources. He received the B.Eng. degree in electrical engineering from Universiti Teknologi MARA, Malaysia, in 2006. He is a student member of IEEE and also member of the Board of Engineers Malaysia. His research interests include the field of power electronics, motor drives, industrial applications and industrial electronics. He can be contacted at email: swahnory80@gmail.com.



Rahimi Baharom    is a lecturer in School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Malaysia since 2009; and He has been a senior lecturer since 2014. He received the B.Eng. degree in electrical engineering and the M.Eng. degree in power electronics, both from Universiti Teknologi MARA, Malaysia, in 2003 and 2008, respectively; and Ph.D. degree in power electronics also from Universiti Teknologi MARA, Malaysia in 2018. He is a senior member of IEEE and also a corporate member of the Board of Engineers Malaysia and the member of Malaysia Board of Technologists. His research interests include the field of power electronics, motor drives, industrial applications and industrial electronics. He can be contacted at email: rahimi6579@gmail.com.



Nur Hidayah Abdullah    is a postgraduate student in School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Malaysia since 2016. She received the B.Eng. degree in electrical engineering from Universiti Teknologi MARA, Malaysia, in 2020. She is a student member of IEEE. Her research interests include the field of power electronics, motor drives, industrial applications and industrial electronics. She can be contacted at email: hidayah0897@gmail.com.